REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
06-06-2014	Final Report	21-Aug-2006 - 20-Feb-2014

4. TITLE AND SUBTITLE
Final Performance Report: Quantum Computation and Simulation Using Neutral Fermionic Atoms

5a. CONTRACT NUMBER
W911NF-06-1-0398

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
48771-PH-PCS.21

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We observed the Efimov effect – the existence of a series of bound three body states related to one another by a universal geometric scaling factor – in a three-component Fermi gas. Our work was the first to observe, in any physical system, an excited Efimov trimer state. In related work, we created a degenerate Fermi gas with SU(3) symmetry, a first step toward the quantum simulation of phenomena in QCD such as color superconductivity. Working with two-component Fermi gases, we demonstrated that narrow Feshbach resonances could be used to

15. SUBJECT TERMS
Fermi Gas, Feshbach Resonance, Efimov Effect, Atomic Clocks, Quantum Simulation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Kenneth O'Hara
					19b. TELEPHONE NUMBER
					814-865-7259

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Performance Report: Quantum Computation and Simulation Using Neutral Fermionic Atoms

ABSTRACT

We observed the Efimov effect – the existence of a series of bound three body states related to one another by a universal geometric scaling factor – in a three-component Fermi gas. Our work was the first to observe, in any physical system, an excited Efimov trimer state. In related work, we created a degenerate Fermi gas with SU(3) symmetry, a first step toward the quantum simulation of phenomena in QCD such as color superconductivity. Working with two-component Fermi gases, we demonstrated that narrow Feshbach resonances could be used to explore Fermi gases with energy and momentum dependent s-wave interactions. We also observed, for the first time, an s-wave collisional frequency shift of a clock transition in a Fermi gas when a spatially inhomogeneous excitation field is used to interrogate the atoms. This work is directly relevant to state-of-the-art optical lattice clocks where spatial inhomogeneities in the clock field are non-negligible since the field varies over the scale of an optical wavelength. Toward the study of strongly correlated Fermi gases, we have demonstrated the rapid control of interactions in a Fermi gas which will allow for diagnostics of strongly correlated Fermi gases of 6-Li and have implemented a site-resolved 2D triangular/honeycomb optical lattice which should permit the observation of anti-ferromagnetic ordering in the Hubbard model.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
06/02/2014	6.00	Eric Hazlett, Yi Zhang, Ronald Stites, Kurt Gibble, Kenneth O’Hara. s-Wave Collisional Frequency Shift of a Fermion Clock, Physical Review Letters, (4 2013): 0. doi: 10.1103/PhysRevLett.110.160801
06/02/2014	7.00	J. Huckans, J. Williams, E. Hazlett, R. Stites, K. O’Hara. Three-Body Recombination in a Three-State Fermi Gas with Widely Tunable Interactions, Physical Review Letters, (04 2009): 0. doi: 10.1103/PhysRevLett.102.165302
06/02/2014	8.00	E. L. Hazlett, Y. Zhang, R. W. Stites, K. M. O’Hara. Realization of a Resonant Fermi Gas with a Large Effective Range, Physical Review Letters, (01 2012): 0. doi: 10.1103/PhysRevLett.108.045304
06/02/2014	9.00	J. Williams, E. Hazlett, J. Huckans, R. Stites, Y. Zhang, K. O’Hara. Evidence for an Excited-State Efimov Trimer in a Three-Component Fermi Gas, Physical Review Letters, (09 2009): 0. doi: 10.1103/PhysRevLett.103.130404
06/02/2014	10.00	K.M. O'Hara, R.W. Stites. The Verdet constant of undoped Y$_3$Al$_5$O$_12$ in the near infrared, Optics Communications, (09 2012): 0. doi: 10.1016/j.optcom.2012.06.008
07/31/2012	1.00	J. Williams, J. Huckans, R. Stites, E. Hazlett, K. O’Hara. Preparing a highly degenerate Fermi gas in an optical lattice, Physical Review A, (07 2010): 11610. doi: 10.1103/PhysRevA.82.011610
07/31/2012	2.00	K. M. O'Hara. Realizing analogues of color superconductivity withultracold alkali atoms, New Journal of Physics, (06 2011): 0. doi:

TOTAL: **7**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

The Eimov Effect in a Fermi Gas; 42nd Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT on Jan. 5, 2012.

Measuring the Collisional Frequency Shift in a Fermi Gas; Georgia Institute of Technology, Georgia Tech Quantum Institute Seminar on November 14, 2011.

Modeling Nuclei and Neutron Matter with Ultracold Atoms, The Pennsylvania State University, Physics Colloquium on September 29, 2011.

Measuring the Collisional Frequency Shift in a Fermi Gas; University of Maryland, Joint Quantum Institute Seminar on September 19, 2011.

Modeling Nuclei and Neutron Matter with Ultracold Atoms; University of Notre Dame, Physics Colloquium on September 14, 2011.

Modeling Nuclei and Neutron Matter with Ultracold Atoms; Cornell University, Laboratory of Atomic and Solid State Physics Seminar on August 30, 2011.?

Measuring the Collisional Frequency Shift in a Fermi Gas; XIII Cross?Border Laser Science, Rochester, NY on June 11, 2011.

Interaction Energy Near a Narrow Feshbach Resonance; Aspen Center for Physics, Workshop on Few? and Many?Body Physics in Cold Quantum Gases Near Resonances on June 6 ? 10, 2011.

Multi?component Fermi Gases in a Honeycomb Lattice; University of Chicago Center in Beijing, Conference on Novel Quantum States in Condensed Matter on September 2, 2010.

Mimicking Dirac Fermions with up to Three Flavors Using Ultracold Atoms; Aspen Center for Physics, Workshop on Critical Behavior of Lattice Models in Condensed Matter and Particle
Physics on June 10, 2010.

Efimov Trimers with Large but Unequal Scattering Lengths; ITAMP, Harvard, Efimov States in Molecules and Nuclei: Theoretical Methods and New Experiments on October 19, 2009.

Stability of a Fermi Gas with 3 Spin States; Bonn University, The 19th International Conference on Few?Body Problems in Physics on August 31, 2009.

Quantum Simulations using Fermionic Atoms in an Optical Lattice; Aspen Center for Physics, Quantum Computing and Simulation Workshop on May 29, 2009.

Experiments with an Ultracold Three?Component Fermi Gas; Research Triangle Park, NC, Workshop on Nearly Perfect Quantum Fluids on April 6, 2009.

Bose?Einstein Condensation and Degenerate Fermi Gases; American Physical Society, APS March Meeting Tutorial on March 15, 2009.

Experiments with an Ultracold Three?Component Fermi Gas; Snowbird, Utah, Physics of Quantum Electronics on January 6, 2009.

Adding Color to a Fermi Gas: the Efimov Effect and Color Superconductivity; University of Toronto, Physics Quantum Optics Seminar on December 1, 2008.

A Colorful Fermi Gas; Pennsylvania State University, CAMP Seminar on November 4, 2008.

Simulating Condensed Matter Physics with Ultracold Atoms; University of Illinois, Quantum Information Science Seminar on February 20, 2008.

Quantum Bits, Quantum Magnetism and Superconductivity: The Exotic World of Fermionic Atoms in an Optical Lattice; University of Delaware, Atomic, Molecular and Optical Physics Seminar on November 19, 2007.

Quantum Simulation of the Hubbard Model using Ultra?Cold Atoms; Regoupement Qubcois sur les Materiaux de Pointe (RQMP), RQMP Summer School on August 3, 2007.

Realizing the 2D Hubbard model using 6Li; The Canadian Institute for Advanced Research, Workshop on Quantum Simulation in February 2007.

Number of Presentations: 22.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
06/02/2014	11.00	E.L. Hazlett, Y. Zhang, R.W. Stites, K. Gibble, K.M. O'Hara. S-Wave Clock Shift for Fermions, 43rd Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics . 06-JUN-12, . : ,
06/02/2014	12.00	Y. Zhang , E.L. Hazlett , R.W. Stites, K.M. O'Hara. Realization of a Resonant Fermi Gas with a Large Effective Range, 43rd Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics . 07-JUN-12, . : ,
06/02/2014	13.00	E.L. Hazlett, J.R. Williams, R.W. Stites, Y. Zhang, K.M. O'Hara, J.H. Huckans. Efimov Physics in a 6Li Gas, 41st Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics . 27-MAY-10, . : ,
06/02/2014	14.00	J.R. Williams, E.L. Hazlett, J.H. Huckans, R.W. Stites, Y. Zhang, K.M. O'Hara. The Efimov Effect and Color Superconductivity in a Three-State Fermi Gas, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics. 21-MAY-09, . : ,
06/02/2014	15.00	J.R. Williams, J.H. Huckans, R.W. Stites, E.L. Hazlett, K.M. O'Hara . Stable mixtures of 6Li fermions in the three lowest energy spin states, 39th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics . 29-MAY-08, . : ,
06/02/2014	16.00	E.L. Hazlett, J.H. Huckans, J.R. Williams, R.W. Stites, K.M. O'Hara . Dynamically adjustable box-like potentials for ultracold atoms, 39th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics . 27-MAY-08, . : ,
06/02/2014	17.00	R.W. Stites, J.R. Williams, E.L. Hazlett, J.H. Huckans, K.M. O'Hara . A High-Power, All-Solid-State Laser Source for Laser Cooling of Lithium, 39th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics. 27-MAY-08, . : ,
06/02/2014	18.00	J.R. Williams, R. Stites, J.H. Huckans, E.L. Hazlett, K.M. O'Hara . Preparing Fermions in an Optical Lattice at Ultra-Low Temperature, 38th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics. 07-JUN-07, . : ,
07/31/2012	3.00	Y. Zhang, E. L. Hazlett, R. W. Stites, K. M. O'Hara. Efficient Generation of Pure High-Order Laguerre-Gaussian Laser Beams, APS Division of Atomic, Molecular and Optical Physics. 14-JUN-11, . : ,
07/31/2012	4.00	R. W. Stites, K. M. O'Hara. A High Power Amplifier for a Single Mode 1064 Laser, APS Division of Atomic, Molecular and Optical Physics . 14-JUN-11, . : ,
07/31/2012	5.00	E. L. Hazlett, Y. Zhang, R. W. Stites, K. M. O'Hara. Three-Body-Recombination Interference Minima in the Midst of Three Overlapping Feshbach Resonances, APS Division of Atomic, Molecular and Optical Physics . 15-JUN-11, . : ,

TOTAL: **11**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
06/02/2014 19.00	Eric L. Hazlett, Yi Zhang, Ronald W. Stites, Kurt Gibble, Kenneth M. O'Hara. s-Wave collisional frequency shift of a fermion clock, 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC). 21-JUL-13, Prague, Czech Republic. : ,
TOTAL:	**1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
06/02/2014 20.00	L. H. Haddad, K. M. O'Hara, Lincoln D. Carr. The nonlinear Dirac equation: Relativistic vortices andexperimental realization in Bose Einstein condensates, ArXiv e-prints (10 2012)
TOTAL:	**1**

Number of Manuscripts:

Books

Received	Book
TOTAL:	

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Jason R. Williams	0.50	
Ronald W. Stites	1.00	
Eric L. Hazlett	1.00	
Yi Zhang	1.00	
Andrew Marcum	0.13	
Arif Mawardi Bin Ismail	0.07	
FTE Equivalent:	**3.70**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
John H. Huckans	0.30
FTE Equivalent:	**0.30**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Kenneth M. O'Hara	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Kang Woo Bae	0.10	Physics
Bradley Cochran	0.05	Physics
Kristina Calloday	0.05	Physics
Clay Long	0.05	Physics
Emily Kremmel	0.05	Physics
FTE Equivalent:	**0.30**	
Total Number:	**5**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 5.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 4.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 3.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Jason R. Williams

Eric L.Hazlett

Ronald W. Stites

Total Number: 3

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

Summary of Important Scientific Results

Production of Degenerate Fermi Gases of ^{6}Li and Bose-Einstein Condensates of ^{6}Li$_2$

At the beginning of this award, funding was used in part for the construction of a new experimental apparatus capable of rapidly producing quantum degenerate ^{6}Li Fermi gases. Our group now prepares highly-degenerate Fermi gases by evaporatively cooling a two-state mixture of fermionic ^{6}Li atoms confined in an optical trap. An optical dipole trap formed at the intersection of two 80 Watt beams of 1064 nm laser light is directly loaded from a ^{6}Li magneto-optical trap. Once loaded, we prepare a 50/50 mixture of atoms in the two lowest hyperfine states and utilize a Feshbach resonance at 834 G to enhance elastic collisions. The high collision rate permits rapid and efficient evaporative cooling as the depth of the optical trap is reduced. This technique, which was developed by the PI [1–4], allows for rapid preparation of highly-degenerate samples (in $< 4\,\mathrm{s}$) and does not require the complexities of an additional atomic species or a magnetic trap. To achieve our lowest temperatures, we perform our final stage of evaporative cooling at a magnetic field of 760 G so that we are on the BEC side of the Feshbach resonance and populate, by three-body recombination, the weakly bound ^{6}Li$_2$ molecular states associated with the Feshbach resonance. These ^{6}Li$_2$ molecules which are composite bosons can form a Bose-Einstein condensate at sufficiently low temperatures. The bimodal distribution which appears in momentum space when the condensate forms is seen in Fig. 1. We can produce highly-degenerate two-component Fermi gases from this molecular BEC by adiabatically sweeping the magnetic field from the BEC side of the Feshbach resonance to the BCS side [5].

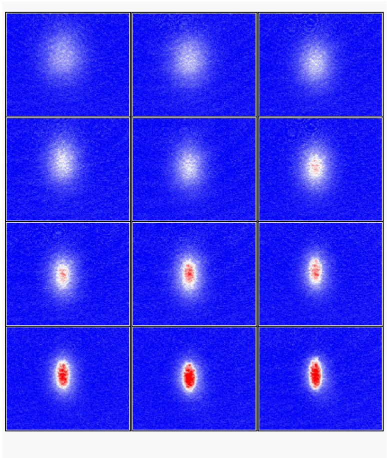


Figure 1: Formation of a Bose-Einstein condensation of ^{6}Li$_2$ molecules in our apparatus.

Universality in a Three-Component Fermi Gas

Working in the context of nuclear physics in the early 1970's, Vitaly Efimov predicted that quantum mechanical three-body systems with resonant or near-resonant short range interactions have universal low energy properties that do not depend on the detailed structure of the interaction potential. Efimov found that when the s-wave scattering length diverges, an infinite series of three-body bound states (i.e. trimer states) occur. The trimer states are invariant under discrete scale transformations with a universal scaling factor of 22.7 [6–8]. When the s-wave scattering length is infinite, there are infinitely many weakly bound Efimov trimers with a geometric spectrum and an accumulation point at the three-particle threshold (i.e. $\left|E_b^{(n)}\right| = (1/22.7)^{2n}\left|E_b^{(0)}\right|$). For finite scattering lengths, all low-energy three-body scattering observables exhibit a log-periodic dependence on the scattering length, a direct consequence of the discrete scale invariance [9]. While certain nuclei such as the triton (pnn), or halo nuclei like ^{20}C (consisting of a tightly bound core ^{16}C nucleus plus two valence neutrons), may be examples of ground state Efimov trimers in

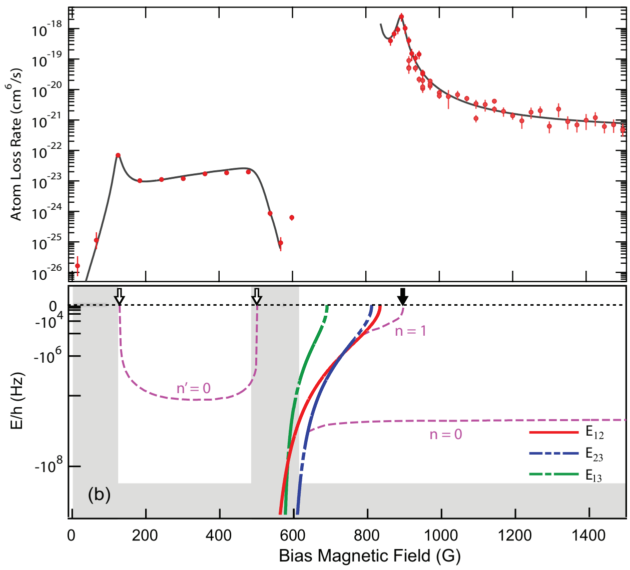


Figure 2: Discovery of Efimov trimers in a three-component Fermi gas of ^{6}Li atoms. (a) We observed resonant enhancement of three-body relaxation at fields of 130, 500, and 895 G. (b) These resonances indicate where a ground-state (dashed magenta lines labeled $n = 0$) or first-excited-state (dashed magenta lines labeled $n = 1$) Efimov trimer crosses the three-atom scattering threshold.

nuclear physics, Efimov's prediction that these systems exhibit a universal discrete scaling symmetry cannot be easily tested since the interaction potentials are not tunable.

In systems of ultracold atoms, on the other hand, magnetically tunable Feshbach scattering resonances permit adjustment of the s-wave scattering length over an extraordinarily broad range. The first evidence for a ground state Efimov trimer in a system of ultracold atoms was observed in a ^{133}Cs Bose gas [10]. However, prior to our work, a first-excited Efimov trimer had not been observed in any physical system. (There had been a claim that a ground and first-excited Efimov trimer had been observed in a ^{7}Li gas [11]. However, further characterization of the Feshbach resonance in ^{7}Li revealed that the resonance attributed to the first excited Efimov trimer was, in fact, the location of the Feshbach pole instead [12].)

In a paper published in *Physical Review Letters* [13] we reported on our measurement of the three-body recombination rate in a three-component Fermi gas of ^{6}Li atoms with equal populations in the three lowest-energy hyperfine states as a function of magnetic field. The three pairwise scattering lengths in this mixture exhibit overlapping Feshbach resonances. As a function of magnetic field, we observed resonances in the three-body recombination at fields of 130 and 500 G as seen in Fig. 2(a). The resonance at 130 G had also been reported by Selim Jochim's group in Ref. [14] who were performing independent, concurrent experiments with the same three-state mixture. Several theoretical papers which followed interpreted the resonances we observed as being due to a ground-state Efimov trimer (dashed lines in Fig. 2(b) labeled $n' = 0$) intersecting the three-atom scattering threshold at 130 G and again at 500 G (open arrows in Fig. 2(b)) [15–18].

In a second experiment performed at much lower temperature ($T < 30\,\mathrm{nK}$), we could access much larger scattering lengths and observed resonantly enhanced three-body recombination of the same three-state mixture near 895 G (see Fig. 2(b)) where the average value of the scattering lengths had increased by a factor of approximately 22.7 over the average value at 130 G or 500 G. In this case, three-body recombination is enhanced by the *first-excited* state Efimov trimer (dashed line in Fig. 2(b) labeled $n = 1$) crossing the three-atom threshold (solid arrow in Fig. 2). This result was reported in *Physical Review Letters* [19]. By comparing our measurement of the three-body recombination rate for fields $\gtrsim 900\,\mathrm{G}$ with predictions of a low-energy effective field theory, we can extract a single complex-valued three-body parameter that accounts for the short-range physics. The effective field theory can then predict all three-body observables using as input the three scattering lengths and the three-body parameter we determined [20]. We believe we now understanding the three-body physics in this three-state mixture whenever the scattering lengths are large (compared to the van der Waals length scale ℓ_{vdW}). It appears that the ground and excited Efimov trimers associated with the three resonant loss features we observe are all part of the same infinite series of Efimov trimer states. Thus, universality survives in this system even though we have crossed through "non-universal" regions where the scattering lengths have become comparable to (or even smaller than) ℓ_{vdW}. Measurement of the three body parameter for the ground and first-excited Efimov trimer state indicates that the discrete scaling parameter in this system is 21.6, close to the value of 22.7 predicted by Efimov. Thus, our experiments have allowed for quantitative tests of universality in three-body quantum systems with resonant short range interactions, systems of interest in atomic, molecular, nuclear and particle physics.

Realization of a Three-Component Fermi Gas with SU(3) Symmetry

For magnetic fields $B \gg 200\,\mathrm{G}$, ^{6}Li is in the Paschen-Back regime where the hyperfine states become increasingly electron-spin polarized (the three states we investigate correspond to the three spin states of the spin-1 nucleus). Thus, as the magnetic field is increased, all three of the pairwise scattering lengths asymptotically approach the triplet scattering length a_t which, for ^{6}Li, has the large negative value $a_t = -2140\,a_0$. The interactions in this three state mixture at high field therefore become invariant under rotations of the three component spinor wavefunction (i.e. are SU(3) invariant). Superfluidity in such a system with SU(3) symmetry would be particularly interesting to study because Cooper pairing with three different pairing partners could occur and there also can be a competition between Cooper pairing and trimer formation. The actual pairing pattern favored by nature is difficult to determine and there are a number of predictions for the different phases that may be observed in this system [21–30]. This system shares some similarities with the low-temperature and high-density portion of the phase diagram in QCD for quark matter. For example, it has been proposed that an analog of the color-superconducting-to-baryon formation phase transition could be observed with a degenerate three-component Fermi gas [24].

As a first step toward realizing such a "color" superfluid phase, we have demonstrated that a quantum degenerate three-component Fermi gas with an approximate SU(3) symmetry can be prepared in a three-component ^{6}Li gas. We have produced an incoherent three-component mixture of ^{6}Li fermions in the three lowest-energy spin states in a 1500 G magnetic field and at a temperature $T = 0.28(6)T_F$ where T_F is the Fermi temperature. For this magnetic field, the difference in mean field energies is more than an order of magnitude smaller than any other energy scale in the system. Thus, the gas has an approximate SU(3) symmetry which will become an even better approximation as the field strength is increased. This result was also reported in Ref. [19].

Preparation of highly-degenerate Fermi gases in an optical lattice

We have also investigated theoretically a technique for cooling fermionic atoms in an optical lattice to temperatures $T \sim 10^{-3}T_F$. The cooling scheme is based on concentrating the entropy of the system in the second band of the optical lattice and then selectively removing the atoms (and the entropy) in the second band in an irreversible way. To concentrate entropy in the second band we begin with a degenerate Fermi gas $T \sim 0.1T_F$ confined in a box-like external potential (i.e. the potential $V_{\text{ext}} \propto r^{2\ell}$ for $\ell \gg 1$) and adiabatically load the atoms into an optical lattice where the density of lattice sites is smaller than the atomic density so that the second band is partially occupied. In this case, the Fermi surface lies in the second band and, if a box-like potential is used, the first band has exactly unit occupancy to a high precision. Atoms are then selectively removed from the second band by transferring atoms from the 2$^{\text{nd}}$ to the 4$^{\text{th}}$ band (by amplitude modulation of the lattice beams) where they are allowed to escape the external potential. Atoms left in the first band are near zero entropy. From numerical modeling we find that temperatures $T \approx 0.003T_F$ can be achieved if a potential $V_{\text{ext}} \propto r^{2\ell}$ with $\ell > 8$ is used. We plan to create this potential by confining atoms inside hollow blue-detuned Laguerre-Gaussian laser beams (see below). The theoretical results appeared in *Physical Review A*(*Rapid Communications*) [31].

Ultracold Collisional Frequency Shifts of Fermi-Based Atomic Clocks

At ultracold temperatures, atom-atom interactions occur only through s-wave collisions, which are allowed for bosons but forbidden for identical fermions by the Pauli exclusion principle. Such shifts are the primary limitation to the accuracy of clocks (which utilize bosons) that establish international atomic time [32, 33]. This suggests that ultracold fermions are better suited for precision metrology [34–38], and quantum memory [39–41], applications that require coherent superpositions of atomic states, unperturbed by collisions. Previously, it was reported that identical spin-1/2 fermions cannot have an ultracold interaction shift (UIS) [35], even for fermions that had become distinguishable due to dephasing [42]. However, recent theoretical work predicted that a UIS occurs for fermions because inhomogeneity of the excitation field generally makes the particles distinguishable [43–45].

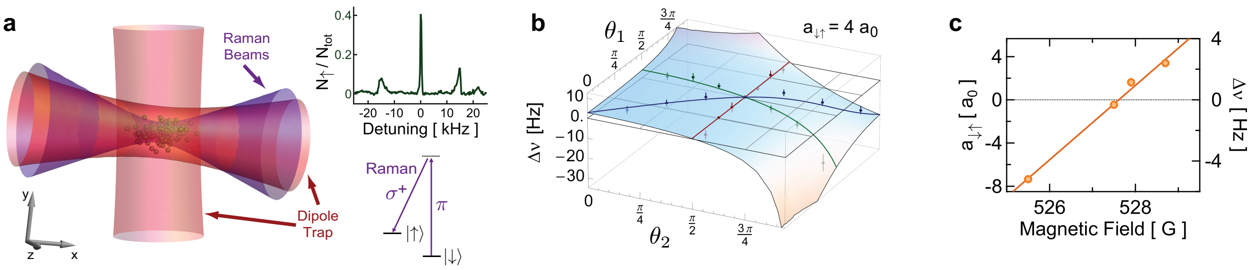


Figure 3: Observation of the s-wave collisional frequency shift of a spin-1/2 Fermi gas. To measure the collisional frequency shift in a ^{6}Li gas, we begin with a spin-polarized Fermi gas and drive a spatially inhomogeneous two-photon Raman transition using focused co-propagating beams.

During this grant period, we experimentally observed, for the first time, an ultracold interaction shift in an atomic clock based on fermions. In doing so, we demonstrated that a fermion UIS, while suppressed compared to bosons, is not excluded. Rather, inhomogeneities invariably present in the clock excitation field generally result in a UIS of an ultracold spin-1/2 Fermi gas (Fig. 3). To impose inhomogeneity, we drive the clock transition using a two-photon Raman transition where the Raman laser beams are focused to a size comparable to the atomic cloud (see Fig. 3). We use Ramsey spectroscopy to clearly distinguish the novel character of the fermion UIS [43] from that of the boson UIS, or the p-wave collision shift of a cold Fermi gas [46]. By tuning the s-wave scattering length through zero near a Feshbach resonance (Fig. 3(c)), we show that the shifts we detect are s-wave and not p-wave. The shift exhibits novel behavior in that it is insensitive to the difference of the spin populations during the interrogation time [43], in stark contrast with the collision shift of bosons or p-wave shifts of fermions [46]. This corresponds to an insensitivity of the shift $\Delta\nu$ to variation of first pulse area θ_1, which determines the population difference (Fig. 3(b)). Instead, the fermion UIS depends strongly on the sensitivity with which the acquired phase is read out. Colliding pairs of atoms experience equal and opposite frequency shifts. These shifts cancel if each atom is read-out with equal sensitivity. Thus, the shift can be zeroed if the second pulse area $\theta_2 \simeq \pi/2$ (Fig. 3(b)). Interestingly, we discovered in this work that correlations between Rabi frequencies and collisional shifts that different atoms experience perturb this result, adjusting the pulse area θ_2 required for zero shift. The UIS is naturally smaller for fermions as compared to bosons, generally non-zero, and vanishes for clock operating parameters near those optimal for peak stability. The fermion UIS we observe in the resolved sideband regime (Fig. 3(a) inset) directly applies to optical lattice clocks [36], for which the spatial field inhomogeneity is naturally large at optical frequencies. Indeed, the inhomogeneity artificially introduced in our experiment was comparable to that in Yb and Sr lattice clocks [47–51]. While the dominant shifts observed so far in Yb and Sr optical lattice clocks [47–51] are consistent with p-wave collisions, the s-wave shift will become more significant as the p-wave shift is minimized in these systems either by lowering the temperature or by adjusting θ_1 near $\pi/2$ where the p-wave shift is zeroed. A manuscript describing this work appeared in *Physical Review Letters* [52].

Suppression of Collisional Shifts with Strong Interactions

In more recent work, we have observed that longer coherence times occur in a many-body spin-1/2 Fermi gas when the system becomes strongly interacting. This can be understood in the context of two spin-1/2 atoms in trap states ψ_a and ψ_b. The two-atom spin basis that diagonalize the interaction Hamiltonian is the singlet-triplet basis (Fig. 4(a)). The anti-symmetric singlet state corresponds to a symmetric spatial wavefunction which experiences an interaction shift $2g$. The matrix element coupling the triplet and singlet states is proportional to the inhomogeneity $\Delta\Omega = (\Omega_a - \Omega_b)/2$ of the driving clock field, while coupling between triplet states is proportional to the average Rabi frequency $\bar{\Omega} = (\Omega_a + \Omega_b)/2$. For weak interactions, the phase acquired by the singlet state, which is read-out in Ramsey spectroscopy when using an inhomogeneous field, produces a collisional frequency shift. However, for sufficiently strong interactions ($2g \gg \bar{\Omega}$), the singlet state can be spectroscopically resolved and the clock field only drives transitions between the triplet states which are non-interacting. Thus, strong interactions actually provide a mechanism to eliminate collisional interaction shifts in a Fermi gas. This has important ramifications for optical lattice clocks which utilize fermionic isotopes since both increased stability and accuracy can be achieved by maximizing the atom number. We have observed that in a many-body spin-1/2 Fermi gas, Rabi oscillations driven by an inhomogeneous clock field persist with less dephasing as the s-wave scattering length is increased (Fig. 4(b)). With increased interactions we are beginning to resolve the interaction gap between pairwise singlet and triplet states. This work is not yet published, a manuscript is in preparation. Similar results were reported for Sr [50]. However, the origin of the shifts in Sr may be due to p-wave collisions which would require a re-interpretation of the results in Ref. [50].

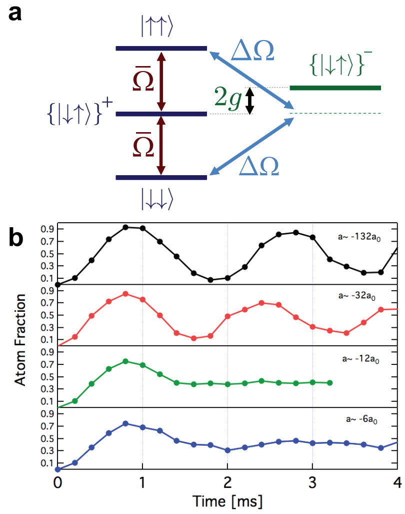


Figure 4: Observation of strong interactions producing long coherence times in a spin-1/2 Fermi gas. For sufficiently strong interactions, excitation to the two-body spin-triplet state is spectroscopically resolved from excitation to the two-body spin-singlet state.

Realizing Analogs of Color Superconductivity in an Ultracold Fermi Gas

We published a paper in the *New Journal of Physics* as part of a "Focus on Strongly Correlated Quantum Fluids: from Ultracold Quantum Gases to QCD Plasmas" special issue [53]. We described how a three-component gas below the superfluid critical temperature can be prepared in an optical lattice. To realize an SU(3)-symmetric system, we show how pairwise interactions in the three-component atomic system can be made equal by applying radio-frequency and microwave radiation. Finally, motivated by the aim to make more accurate models of quark matter, which have color, flavor and spin degrees of freedom, we discuss how an atomic system with $\mathrm{SU}(2) \bigotimes \mathrm{SU}(3)$ symmetry can be achieved by confining a three-component Fermi gas in the p-orbital band of an optical lattice potential and rotating each lattice site about its own center.

Energy Dependent Interactions in a Fermi Gas

We have demonstrated that energy- and momentum-dependent interactions in a Fermi gas can be realized by working near a narrow (rather than broad) Feshbach resonance. We have measured the interaction energy and three-body recombination rate for a two-component Fermi gas near a narrow Feshbach resonance and found both to be strongly energy dependent. Even for de Broglie wavelengths greatly exceeding the van der Waals length scale, the behavior of the interaction energy as a function of temperature cannot be described by atoms interacting via a contact potential. Rather, energy-dependent corrections beyond the scattering length approximation are required, indicating a resonance with an anomalously large effective range. We also noted that for fields where the molecular state is above threshold, the rate of three-body recombination is enhanced by a sharp, two-body resonance arising from the closed-channel molecular state which can be magnetically tuned through the continuum. This narrow resonance can be used to study strongly correlated Fermi gases that simultaneously have a sizable effective range and a large scattering length. Such systems are relevant for determining the equation of state for neutron star matter (neutron-neutron s-wave collisions have both a large effective range and scattering length). Also, ultracold Fermi gases with resonant interactions and a large effective range can exhibit novel forms of superfluid phases (e.g. the breached-pair phase) and may have the highest critical temperatures for superfluidity ever observed. Our study appeared in *PRL* [54].

Relativistic Vortices in Bose-Einstein Condensates

Working with Prof. Lincoln Carr and Laith Haddad from the Colorado School of Mines, we have proposed a method to excite relativistic vortices in a Bose-Einstein condensate confined in a honeycomb lattice potential and have determined the stability of these vortices [55]. A BEC is initially prepared at a Dirac point of the honeycomb lattice band structure and having amplitude only in the A sublattice sites. Ring-vortices (a soliton-vortex pair) can be generated by transferring angular momentum to the BEC with a Laguerre-Gaussian laser beam and simultaneously modulating the lattice potential such that only the part of the condensate that acquires angular momentum makes a transition between sublattices. The stable vortex which results consists of a vortex in the B sublattice with a soliton in the A sublattice centered on the vortex core. We predict these ring-vortices will be stable for $\sim 1\,\mathrm{sec}$ for realistic experimental parameters. A manuscript describing this work has been submitted to *Physical Review A* [55].

Self Injection Locking of Ring Lasers

We have constructed a new high-power all-solid-state ring-laser source for 1342 nm laser light which employs a novel design (suggested to us by Stephen Gensemer) for obtaining uni-directional, single-frequency operation by self-injection locking. The benefit of this design, generally applicable to any ring laser, is that lossy elements can be moved into an external cavity which operates at low optical power, minimizing loss and achieving higher overall output power. In this technique, a small portion of the ring-laser output is sampled, transmitted through an optical isolator and frequency selective components, and then re-injected through the other port of the output coupler for the ring laser. With a double-end-pumped Nd:YVO_4 gain medium, we attain 3 Watts at a wavelength near 1342 nm which can be frequency doubled and used for Li trapping laser light (see also Ref. [56] for a source without self-injection-locking). As part of this project, we measured the Verdet constant of YAG in the near infrared [57]) and are now preparing a manuscript describing the self-injection-locking technique.

Pure High-Order Laguerre-Gaussian Laser Beams

High order Laguerre-Gaussian (LG) laser beams are useful for transferring angular momentum to cold gases [58–60], trapping neutral atoms in optical dipole traps [61] and increasing the sensitivity of gravitational wave detectors [62, 63]. Our interest is in using a high-order LG beam as a dipole trap to provide a flat-bottomed potential to implement a cooling scheme we previously proposed [31] and to study homogeneous gases in optical lattices.

We have experimentally generated pure, high-order Laguerre-Gaussian laser beams $LG^{p=0}_{l=12}$ using a spiral phase plate and an optical cavity as a spatial filter. Here, l and p are the angular and radial mode numbers respectively. A spiral phase plate with a $12 \times 2\pi$ total phase winding converts a fundamental Gaussian beam to a superposition of $LG^{p}_{l=12}$ beams. A plano-concave optical cavity is then used as a filter to remove all radial modes of the beam except the $p = 0$ mode. This is a non-confocal cavity so that the different transverse modes can be resolved. The measured conversion efficiency is 33.2% and the purity of the generated $LG^{p=0}_{l=12}$ beam is $98.9 \pm 0.3\%$. A manuscript has been submitted to *Optics Communications* [64].

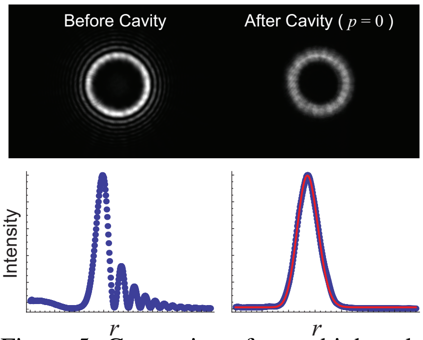


Figure 5: Generation of pure, high-order Laguerre-Gaussian laser beams for an external trapping potential. A gaussian beam transmitted through a spiral phase plate with a $12 \times 2\pi$ phase winding is filtered by a optical cavity to produce a pure LG beam with only one radial mode ($p = 0$).

Rapid Control of Interactions in a Two-Component ^{6}Li Gas

We have developed a novel technique for the rapid control of interactions in a two-component ^{6}Li gas based on driving two-photon Raman transition between different internal states of ^{6}Li. This allows us to rapidly change a two-component mixture from one that is strongly interacting to one that is essentially non-interacting. This can be useful for reconstructing the initial momentum distribution of atoms in the trap by time-of-flight imaging if interactions are extinguished simultaneously with release of atoms from the trap. This would then open up the possibility of novel techniques for characterizing strongly correlated phases of ^{6}Li atoms such as quantum noise interferometry [65] or momentum-resolved photo-emission spectroscopy [66]. Alternatively, if so desired, one can rapidly produce a two-component mixture with large inelastic two-body loss rates starting from a stable, strongly-interacting mixture. This can be useful for probing local spin correlations or for preparing multi-partite entangled states in the steady-state which arises naturally for a thermal, two-component Fermi gas when an s-wave inelastic loss channel exists [67].

To accomplish these goals we have demonstrated that we can transfer atoms between different internal hyperfine states of ^{6}Li such that certain two-component mixtures are weakly interacting, while others are strongly interacting, while other mixtures decay rapidly by two body inelastic collisions. In order for us to consider the scattering properties of different two-state mixtures of ^{6}Li, we use an extremely simple model of the $^6Li_2$ singlet and triplet molecular potentials (treating them simply as square well potentials) and perform full coupled-channel s-wave scattering calculations with these simplistic model potential.

Each possible two-state mixture of the three lowest hyperfine states, states $|1\rangle$, $|2\rangle$ and $|3\rangle$, have no allowed spin-exchange decay channels and each exhibits a broad Feshbach resonance. Thus, these three mixtures are each very well suited to provide strongly interacting mixtures with zero or minimal two-body loss. Among these, the $|1\rangle - |2\rangle$ mixture is the best of these since even a dipolar loss rate, provided p-wave collisions are frozen out, is forbidden for this mixture. Still, the $|1\rangle - |3\rangle$ mixture and the $|2\rangle - |3\rangle$ mixtures have been observed to be quite stable with relatively small dipolar relaxation rate constants.

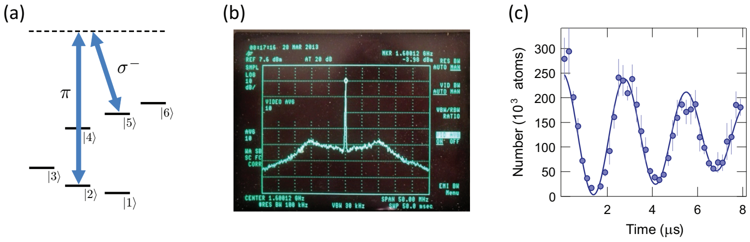


Figure 6: Two-photon Raman transition used to rapidly control interactions in ^{6}Li gas by quickly switching between different two-state mixtures. (a) Two-photon Raman transition transfers population between states $|2\rangle$ and $|5\rangle$. In this case, if a strongly interaction $|1\rangle - |2\rangle$ mixture initially exists, transfer of population from state $|2\rangle$ to state $|5\rangle$ produces a $|1\rangle - |5\rangle$ mixture which is weakly interacting and relatively stable against decay. (b) Beat note between two diode lasers driving the Raman transition as recorded by a spectrum analyzer. (c) Rabi oscillations between states $|2\rangle$ and $|5\rangle$. The decay of contrast is due to the finite size of the Raman beams.

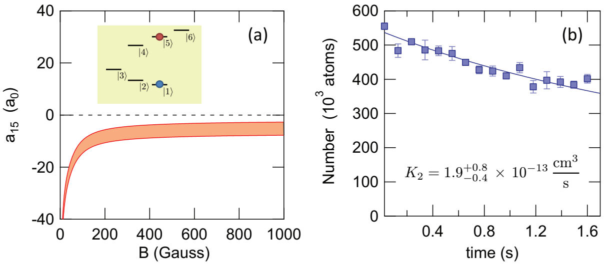


Figure 7: Stable, weakly-interacting two-state mixture of ^{6}Li fermions. (a) The s-wave scattering length a_{15} for a $|1\rangle - |5\rangle$ mixture of ^{6}Li atoms as a function of field as predicted by a simple coupled channels model. The range of scattering lengths shown are for different choices of model parameters. (b) Decay of the $|1\rangle - |5\rangle$ mixture in a gas with an initial density of 3×10^{12} atoms/cm^3 in each spin state. The decay is due to a weak dipolar loss with a measured two-body inelastic loss rate coefficient $K_2 = 1.9^{+0.8}_{-0.4} \times 10^{-13}\mathrm{cm}^3/\mathrm{s}$.

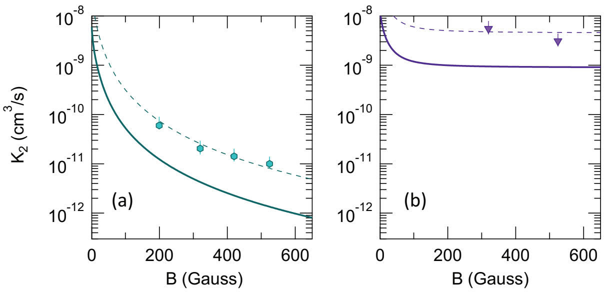


Figure 8: Predicted and measured spin-exchange loss rate coefficients for a $|2\rangle - |5\rangle$ mixture and for a $|2\rangle - |6\rangle$ mixture. (a) The spin-exchange loss rate coefficient predicted by a simple model (solid line) for a $|2\rangle - |5\rangle$ mixture in comparison to measured values. Dashed line shows the rate predicted by the simple model multiplied by a factor of five. (b) Predicted and measured spin-exchange loss rate coefficient for a $|2\rangle - |6\rangle$ mixture.

Dynamically Controllable Triangular/Honeycomb Optical Lattice with Single Site Resolution

A primary goal of the originally proposed research program was to investigate the repulsive Hubbard model and to observe anti-ferromagnetic ordering below the Néel temperature. This has proven to be a significantly challenging problem given the exceptionally low temperature/entropy that must be achieved for fermions confined in a lattice. However, we have made recent experimental progress toward observing the anti-ferromagnetic phase transition.

We have recently implemented a 2D lattice which we can dynamically transform from a triangular to a honeycomb lattice potential. The honeycomb lattice is a bi-partite lattice and a two-component Fermi gas with repulsive interactions should form an anti-ferromagnetic insulating state at sufficiently low temperature. To prepare extremely low entropy samples, we will begin with a highly degenerate band insulating state in the triangular lattice potential which can be prepared with extremely high fidelity due to the large band gap of the band insulator. We will then adiabatically transform the triangular lattice to a honeycomb lattice by adjusting the polarization of the 532 nm laser beams shown in Fig. 9. In the transformation, each site of the triangular lattice splits in two and these separate to ultimately form the honeycomb lattice. During the entire transformation, the spectrum remains gapped and it should be possible to adiabatically transform from the band insulating state in the triangular lattice to a anti-ferromagnetic Mott insulating state in the honeycomb lattice. A further notable feature of this triangular/honeycomb lattice is that the lattice constant is sufficiently large that individual lattice sites can be spatially resolved using off-the-shelf optical components. The figures shown in the upper right hand corner of Fig. 9 demonstrate single site resolution of the lattice potential.

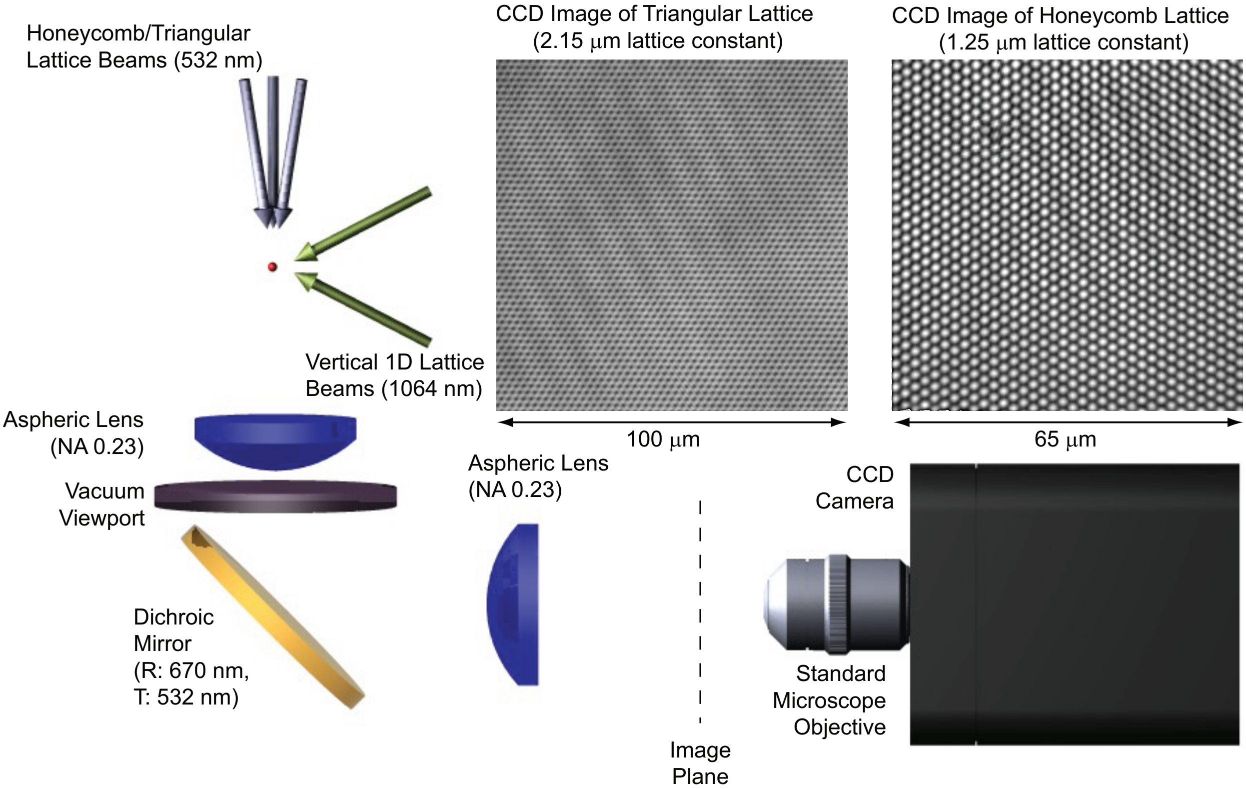
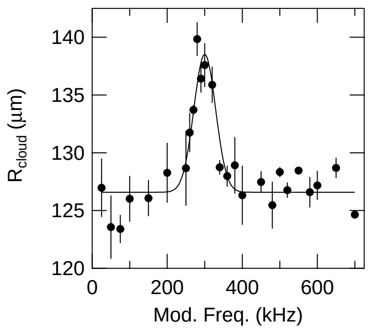


Figure 9: Lattice beams and quantum gas microscope for fermionic ^{6}Li atoms confined in a 2D optical lattice. Atoms are to be tightly confined vertically in the lattice formed from the two 1064 nm laser beams shown in light green to produce a 2D Fermi gas. Three 532 nm laser beams (light blue beams incident from above) form a long-period 2D lattice with either honeycomb or triangular geometry depending on the polarization of the beams. Owing to the large lattice constant, aspheric lenses with a numerical aperture of only 0.23 have sufficient resolution to image individual sites of the 2D lattices. The images in the upper right show the lattice potential imaged through the optical system onto a CCD camera using off-the-shelf microscope objectives of two different magnifications. For the 2D lattices realized in these images, the triangular and honeycomb lattice geometries have a lattice site separation of $2.15\ \mu\mathrm{m}$ and $1.25\ \mu\mathrm{m}$ respectively. The optical system has sufficient resolution to resolve individual lattice sites in either geometry and can observe fields of view containing thousands of sites. In order to image atoms in each site, a deep, short-period optical lattice will be turned on to hold each atom fixed in space while laser cooling light (not shown) is applied, causing the atoms to flouresce. The flourescence will be imaged onto a CCD array for 100's of ms to determine site occupation. It is noteworthy that the triangular lattice can be dynamically transformed into the honeycomb lattice by adjusting the polarizations of the 532 nm beams. Each triangular lattice site splits into double wells which separate until ultimately forming the honeycomb geometry. This ability will be used to prepare anti-ferromagnetic insulating phases at very low entropy.

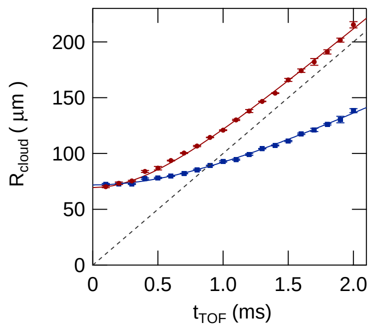
Confinement of ^{6}Li in a Two-Dimensional Triangular Lattice

At the end of the funded grant period, we demonstrated confinement of ^{6}Li atoms in a a two-dimensional triangular lattice. The vertical 1D lattice (to be produced by the 1064 nm laser beams shown in Fig. 9) has not yet been applied. The 2D lattice alone produces a 2D array of one-dimensional confining potentials. Thus, in this potential, we can study the physics of 1D Fermi gases.

To realize a 1D gas, the gas must be confined sufficiently tightly in two directions that the radial confinement energy in the radial direction, $\hbar\omega_\perp$, is larger than all other energy scales in the system, i.e. k_BT, or k_BT_F for a degenerate Fermi gas. In Fig. 10, we demonstrate that we have confined a gas of ^{6}Li fermions sufficiently tightly in two directions to realize the 1D regime. Fig. 10(a) shows our measurement of the radial oscillation frequencies in the tight direction of the tubes by the method of parametric resonance. Here the amplitude of



(a) Parametric Resonance



(b) TOF from Lattice

Figure 10: Realization of 1D thermal gases of ^{6}Li fermions by confinement in a 2D triangular lattice. (a) Parametric resonance demonstrating that the oscillation frequency in the tight radial direction of each lattice site $\omega_\perp \simeq 2\pi \times 150\,\mathrm{kHz}$. (b) Time-of-flight expansion of ^{6}Li atoms from the 2D optical lattice. The clear anisotropic expansion of this non-interacting Fermi gas results from the fact that the zero-point energy in the radial direction of each tube (red) is larger than the thermal energy along the axis of the tube (blue) indicating that the 1D regime has been achieved. The dashed line shows the predicted expansion for a single tube occupying the harmonic oscillator ground state for $\omega_\perp = 2\pi \times 150\,\mathrm{kHz}$ (i.e. the dashed line corresponds to $R_{\mathrm{cloud}} = \sqrt{\frac{\hbar\omega_\perp}{m}}\, t_{\mathrm{TOF}}$).

the 2D lattice beams are modulated at the modulation frequency indicated on the horizontal axis. When the modulation frequency is twice the trap oscillation frequency, atoms are heated significantly. Thus, this data shows the trap oscillation frequency is $\omega_\perp = 2\pi \times 150\,\mathrm{kHz}$. Fig. 10(b) shows time-of-flight expansion of the cloud following release from the lattice. The red filled circles show the radius of the cloud in the direction perpendicular to the axis of the 1D tubes (i.e. parallel to the tight radial directions of the individual 1D tubes) as a function of time of flight, t_{TOF}. The blue filled squares show the radius of the cloud in the direction parallel to the axis of the 1D tubes as a function of t_{TOF}. The red and blue lines are respectively fits to the data. Here the fit to the axial expansion data (blue solid line) is a fit to $R_z = \sqrt{\frac{2k_BT}{m\omega_z^2}}\,\sqrt{1+\omega_z^2\, t_{\mathrm{TOF}}^2}$ allowing us to extract the apparent thermal temperature $T = 1.2\,\mu\mathrm{K}$ and the axial frequency $\omega_z = 2\pi \times 128\,\mathrm{Hz}$. The red solid line, on the other hand, is a single parameter fit to $R_\perp = R_0\,\sqrt{1+v^2\, t_{\mathrm{TOF}}^2}$ where v is taken to be the velocity of expansion for the harmonic oscillator ground state wavefunction assuming $\omega_\perp = 2\pi \times 150\,\mathrm{kHz}$, $v = \sqrt{\hbar\omega_\perp/m}$. The single fit parameter R_0 in this case simply corresponds to the number of tubes that are initially occupied in this direction. Thus, since this expansion asymptotes to the velocity of expansion for the harmonic oscillator ground state, we conclude that the atoms are predominately in the harmonic oscillator ground state in the radial direction of each tube. Furthermore, the very fact that this expansion is dramatically anisotropic indicates that the zero point energy in the radial direction is larger than the apparent thermal energy in the axial direction. From this data we indeed find that $k_B\,(1.2\,\mu\mathrm{K}) \ll \hbar\,(2\pi \times 150\,\mathrm{kHz})$ and the 1D regime has been achieved.

We are in the process of performing radio-frequency spectroscopy on the atoms confined in the lattice in order to determine the distribution of atom number in each of the tubes. It is likely that the data shown in Fig. 10 represents a weakly degenerate Fermi gas. We will have a better idea once our study of radio-frequency spectroscopy is complete.

Having confined ^{6}Li fermions in a 2D triangular lattice, we are now well positioned to apply a 1D lattice in the vertical direction and adiabatically prepare atoms in an anti-ferromagnetic Mott insulating phase.

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